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Cognitive control in context: Working memory capacity and proactive control

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ABSTRACT

Working memory is important for maintaining critical information in an active state to guide future behavior. The executive-attention theory of working memory capacity (WMC; Engle & Kane, 2004) argues that goal maintenance is important for response selection when stimuli are associated with competing responses. Braver, Burgess, and Gray (2007) have labeled this type of preparatory activity proactive control. Previous WMC studies have not allowed individuals to use goal information to prepare a specific response in advance of the stimulus. The current experiment used different versions of a cue-probe task to examine the relationship between individual differences in WMC and proactive control. Across three versions of the AX version of the Continuous Performance Test, the proportion of targets was manipulated to affect both the predictive validity of the A cue and the prepotency of the target response to X probes. The results indicated that the high-WMC individuals used the cue information to prepare responses in advance only when a specific probe was likely to occur. In contrast, the performance of the low-WMC individuals was less dependent upon the cue and more contingent upon overall response frequencies. The results indicate that individual differences in WMC are related to proactive control and anticipation, and important for translating cognition into action.

1. Introduction

The notion of cognitive control has been invoked to explain performance in a number of activities. Broadly defined, cognitive control is the set of mental processes by which information is maintained in a temporary format to guide behavior towards task success, especially if there are competing alternative actions that could be selected instead of the desired target behavior. Braver, Gray, & Burgess (2007) (see also Braver, 2012) proposed a mechanistic account that attempts to synthesize the cognitive control literature. Specifically, their dual-mechanism theory of cognitive control provides a framework for understanding both person- and task-related variations in controlled behavior. Their model is also influenced by knowledge of neurotransmitter and neuroanatomical properties of the human cortex observed in both typical and atypical biological functioning. The current research sought to apply Braver et al.'s model to cognitive control variation observed in individuals varying in working memory capacity (WMC). More specifically, (a) do individuals high in WMC use proactive control to anticipate and prepare a response more often than low-WMC individuals, and (b) do high-WMC individuals adjust their use of proactive control based on the predictive nature of the cue-related information?

2. Executive-attention theory of working memory capacity

Engle and colleagues (Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007; Unsworth & Engle, 2007) have provided evidence that performance on complex working memory span tasks is predictive of behavior in a variety of situations. In a typical complex span task, such as Operation Span (Unsworth, Heitz, Schrock, & Engle, 2005), subjects must mentally solve math problems while also remembering letters for later recall. Variation in the ability to complete these types of tasks is used to measure individual differences in WMC. Not only do individuals high in WMC outperform those low in WMC on a variety of memory tasks, but they also show improved performance on several attention and inhibition tasks (for review, see Redick, Heitz, & Engle, 2007). According to the *executive-attention* theory (Engle & Kane, 2004; Kane et al., 2007), individual differences in WMC reflect variation in goal maintenance and response-conflict resolution.

3. The dual-mechanism theory of cognitive control

While the executive-attention theory has been examined using young adults varying in WMC, Braver et al. (2005, 2007) proposed the dual-mechanism theory of cognitive control initially to account for cognitive aging deficits. The theory derives its name from the two modes of control that are assumed to be responsible for flexible, goal-driven behavior. *Proactive* control involves the active maintenance of information that will help to respond appropriately to upcoming stimulus

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events. This context information could be general task instructions, the identity of previous stimuli, or the relevant information conveyed by previous stimuli or cues that are salient for later behavior. The second control type is *reactive* control. Reactive control involves the reactivation or retrieval of context information that is imperative for the current decision-making; however, reactive control is only engaged in response to the probe or critical stimulus. Proactive control is important for sustaining prior information to bias future responding in a way consistent with expectancies and the schedule of rewards and punishments. However, there may be instances where there is either no predictive information available to help prepare one action versus another, or the cue or warning information that is available for use is unreliable. In these situations, the individual should rely upon reactive control to respond accurately.

Braver et al. (2005) used the AX version of the Continuous Performance Test (AX-CPT) to examine proactive and reactive control modes. Although in the AX-CPT, individual letters are presented visually one at a time, the task is best understood as a series of letters presented in a cue-probe sequence. Subjects are instructed to make a target keypress when the probe letter X immediately follows the cue letter A (Fig. 1). *AX* target sequences occur on the majority of trials (70% of all cue-probe sequences), so an expectancy to make a target response is created when the letter A is presented as a cue. Because AX trials occur on 70% of all trials, this version is denoted hereafter as the *AX-CPT-70*. There are three other possible nontarget trial types on the AX-CPT-70, each occurring on 10% of trials. On an *AY* trial (where Y stands for all non-X letters as probes), the cue A is not followed by an X probe. In addition, on *BX* trials (where B stands for all non-A letters as cues), the probe letter X follows a letter other than A. Finally, on *BY* trials, letters other than A and X are presented sequentially to serve as a baseline condition, because neither the cue nor the probe is associated with the target response (see Table 1 for more information about the probability of the different types of cues, probes, and conditional probabilities for different cue-probe sequences and responses).

As Braver et al. (2007) state, “In the AX-CPT, proactive control means control engaged by the cue, whereas reactive control means control driven by the probe” (p. 81). Thus, subjects using proactive control more often will lead to fewer errors specifically on AX and BX trials, and will also speed correct responses on AX and BX trials, because they have used the cue information to anticipate and prepare a response to the subsequent probe during the cue-probe interval. However, if a subject is engaging in proactive control on an AY trial, he must stop the prepared target response and execute a nontarget response. Thus, AY trials should be more error-prone, and slower for correct trials, because the expected target stimulus does not occur. In contrast,

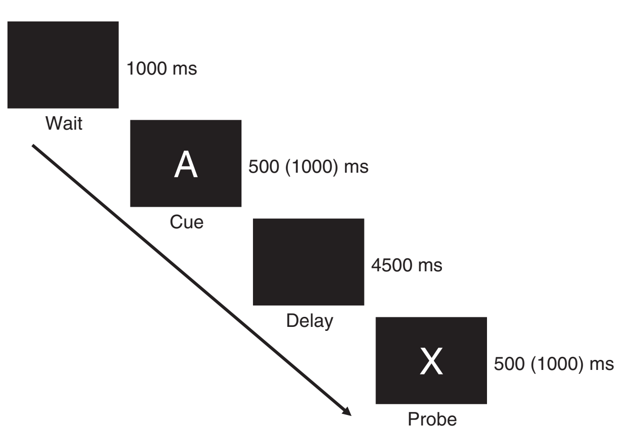

Fig. 1. Example AX target trial sequence from the AX-CPT. For cue and probe screens, the letter was displayed for 500 ms, and the numbers in parentheses (1000 ms) indicate the amount of time since the onset of the letter that the subject had to respond to each letter (a response deadline of 500 ms after the offset of the letter).

Table 1
Stimulus probabilities and predicted control mode for the versions of the AX-CPT.

Type	Freq	*p*(cue)	*p*(probe)	*p*(probe|cue)	*p*(targ|cue)	*p*(targ|probe)	Optimal Mode
AX-CPT-70							
AX	70%	.8	.8	.875	.875	.875	Proactive (targ)
AY	10%	.8	.2	.125	.875	.000	Proactive (targ)
BX	10%	.2	.8	.500	.000	.875	Proactive (non)
BY	10%	.2	.2	.500	.000	.000	Proactive (non)
AX-CPT-10							
AX	10%	.8	.2	.125	.125	.500	Proactive (non)
AY	70%	.8	.8	.875	.125	.000	Proactive (non)
BX	10%	.2	.2	.500	.000	.500	Proactive (non)
BY	10%	.2	.8	.500	.000	.000	Proactive (non)
AX-CPT-40							
AX	40%	.8	.5	.500	.500	.800	Reactive
AY	40%	.8	.5	.500	.500	.000	Reactive
BX	10%	.2	.5	.500	.000	.800	Proactive (non)
BY	10%	.2	.5	.500	.000	.000	Proactive (non)

Note. Type: Trial Type; Freq: Frequency; *p*(cue): probability that the first letter in the Type column appears as a cue; *p*(probe): probability that the second letter in the Type column appears as a probe; *p*(probe|cue): conditional probability that the type of probe appears given the type of cue for that trial type; *p*(targ|cue): conditional probability that a target response is the correct response given the type of cue for that trial type; *p*(targ|probe): conditional probability that a target response is the correct response given the type of probe for that trial type; targ: target response; non: nontarget response.

individuals not engaging in proactive control do not prepare a response during the cue-probe delay, and thus must rely upon a transient reactivation of the cue information when the probe appears. Therefore, subjects engaging less often in proactive control will commit more errors specifically on BX trials, and have slower correct RTs on AX and BX trials. However, on AY trials, not preparing a target response based on the A cue should actually help performance. Thus, when a letter such as F appears as the probe, the subject can and should relatively quickly and accurately respond that it is not a target.

4. Individual differences in WMC as variation in proactive control

Across multiple studies (Braver, Paxton, Locke, & Barch, 2009; Braver et al., 2001, 2005; Paxton, Barch, Racine, & Braver, 2008; Paxton, Barch, Storandt, & Braver, 2006), older adults' performance on the AX-CPT-70 was consistent with reactive control (spared AY performance in either errors or correct RTs relative to young adults, but impaired BX performance), while the young adult groups exhibited performance consistent with engaging in proactive control (fast and accurate AX and BX performance). In addition, Braver et al. (2007) suggested that “individuals with high-WM span… should thus show an increased tendency to use proactive control strategies, but only in the task demands that most require and benefit from such strategies” (p. 89). Moreover, Kane et al. (2007) argued that the “executive-attention view…parallels the dual mechanisms of cognitive control proposed by Braver et al.” (p. 44). That is, although previous research suggests that young adults use proactive control more often than older adults, individual differences in WMC may explain variation in cognitive control observed *within* young adults.

Previous research using a cued-antisaccade task (Unsworth, Schrock, & Engle, 2004), cued-visual search task (Poole & Kane, 2009), and versions of a go/no-go task where subjects must use previous stimuli to determine future targets (Redick, Calvo, Gay, & Engle, 2011) all